Low-noise and Wideband Hot-Electron Superconductive Mixers for THz Frequencies

B.S. Karasik[a], A. Skalare, R. Wyss, W.R. McGrath, B. Bumble, H.G. LeDuc, J.B. Barner, and A.W. Kleinsasser

Center for Space Microelectronics Technology, Jet Propulsion Laboratory, California Institute of Technology

Abstract—Superconductive hot-electron bolometer (HEB) mixers have been built and tested in the frequency range from 1.1 THz to 2.5 THz. The mixer device is a 0.15-0.3 μm microbridge made from a 10 nm thick Nb film. This device employs diffusion as a cooling mechanism for hot electrons. The double sideband noise temperature was measured to be ≤3000 K at 2.5 THz and the mixer IF bandwidth is expected to be at least 10 GHz for a 0.1 μm long device. The local oscillator (LO) power dissipated in the HEB microbridge was 20-100 nW. Further improvement of the mixer characteristics can be potentially achieved by using Al microbridges. The advantages and parameters of such devices are evaluated. The HEB mixer is a primary candidate for ground based, airborne and spaceborne heterodyne instruments at THz frequencies. HEB receivers are planned for use on the NASA Stratospheric Observatory for Infrared Astronomy (SOFIA) and the ESA Far Infrared and Submillimeter Space Telescope (FIRST). The prospects of a submicron-size $YBa_2Cu_3O_{7-\delta}$ (YBCO) HEB are discussed. The expected LO power of 1-10 μW and SSB noise temperature of ≈2000 K may make this mixer attractive for various remote sensing applications.

Fig. 1. Diffusion-cooled HEB receiver performance compared to state-of-the-art heterodyne receiver performance at submillimeter wavelengths.

I. INTRODUCTION

Low noise heterodyne receivers are needed for astrophysical and earth remote-sensing observations at frequencies between about 100 GHz and 3 THz (3 mm to 100 μm wavelength). Niobium (Nb) SIS quasiparticle mixers provide excellent performance up to about the bulk superconductive energy gap frequency f_g of 750 GHz, but are unlikely to work well much above 1 THz (see Fig. 1) [1]. A unique superconducting transition-edge hot-electron bolometer (HEB) mixer has been proposed [2,3] as an alternative to address the THz-regime applications. The HEB mixer is expected to operate up to at least several 10's of THz, due to the relatively frequency independent absorption of rf radiation in a superconductor above the gap frequency. The rf impedance of a superconducting microbridge is expected to be real and independent of frequency from about f_g up to frequencies of visible light. Theory [4] predicts the HEB mixer noise temperature due to the intrinsic thermal-fluctuation noise mechanisms to be very low, so it would be most likely quantum limited at THz frequencies. Also the required local oscillator (LO) power is independent of frequency and can be made very low (less than 100 nW for Nb *diffusion-cooled* devices) for appropriate choice of transition temperature T_c and film sheet resistance. Our appr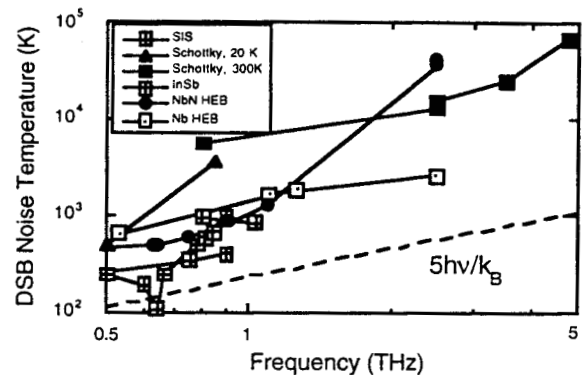oach utilizes ≈ 100 Å thick low-resistivity, high quality Nb films, in which out-diffusion of electrons to normal metal contacts serves as the dominant electron cooling mechanism [3].

II. NOISE PERFORMANCE OF NB HEB MIXERS

We have successfully developed and tested quasioptical *diffusion-cooled* HEB mixers at 1.1 THz and 2.5 THz in heterodyne receivers. Record sensitivity and IF bandwidth were obtained demonstrating the advantages of diffusion-cooled HEB mixers at THz frequencies. These results are described here (see recent publications [5,6] for additional details).

The bolometer devices used in these experiments consist of a 0.30 μm long by 0.15 μm wide microbridge made of a 12 nm thick sputtered-deposited Nb film. The length of the bridge was defined by the gap between the 150 nm thick gold contact pads using a unique self-aligned fabrication process [7]. The surrounding mixer embedding circuit and planar antenna are fabricated from 300 nm thick gold. This process gives automatic registration of the Nb under the gold to provide dependable electrical and thermal contact. This fabrication process produced excellent device parameters: critical temperatures T_c in the range 4.5 K to 6.5 K, transition width ≤ 0.3 K; and sheet resistance 10-20 Ω/sq. The critical current density at 4.2 K was as high as 1.5×10^7 A/cm^2.

Two different quasioptical mixer designs were developed. For 1.1 THz, the mixer consisted of double-dipole antenna with coplanar strip transmission lines located at the focus of a quartz hyperhemispherical lens [5]. The mixer embedding circuit for 2.5 THz used a twin-slot antenna and coplanar waveguide transmission line located at the second focus of an elliptical silicon lens [6] (see Fig. 2). The receiver test system employed either a backward wave oscillator operating at 1105 GHz as a local oscillator (LO) source, or a CO_2-pumped FIR laser to generate LO power at 2522 GHz
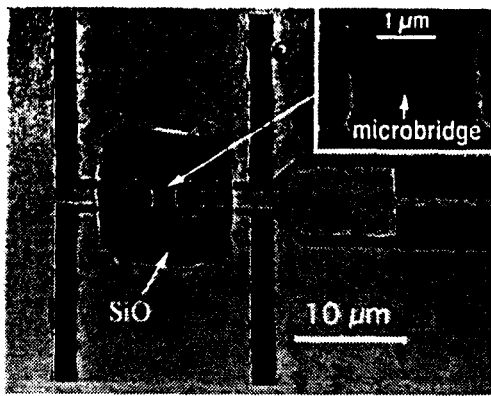
Fig. 2. 2.5 THz Planar mixer circuit consisting of the twin-slot antenna and coplanar waveguide transmission line. To the right are the IF and dc lines with an integrated rf choke filter.

using methanol vapor. A vacuum box containing two blackbody loads with similar emissivities was designed and built for Y-factor measurements of the receiver noise temperature. The box is connected to the LHe vacuum cryostat, allowing operation without a pressure window in the signal path. The box and cryostat are evacuated to remove the effect of atmospheric absorption which is significant above 1 THz. The 1.1 THz receiver used a cooled HEMT IF amplifier centered at 1.5 GHz, and the 2.5 THz receiver used a similar amplifier centered at 2.1 GHz.

III. IF BANDWIDTH IN NB HEB DIFFUSION-COOLED MIXERS

Since these bolometer mixers use outdiffusion of hot electrons as the cooling mechanism, the thermal relaxation τ_T time should vary as L^2, where L is the microbridge length, for devices shorter than about 0.5 μm [8]. The thermal response time can be estimated from the expression: $\tau_T = L^2/(\pi^2 D)$, where D is the thermal diffusivity of the film. Thus the 3-dB IF bandwidth $f_{3dB} = 1/(2\pi\tau_T)$ should vary as L^{-2}.

The IF bandwidth of several devices varying in length between 0.3 μm and 0.1 μm was measured in mixing experiments at frequencies ≈ 500-600 GHz. As shown in Fig. 3, the bandwidth did indeed vary as L^{-2}, with the
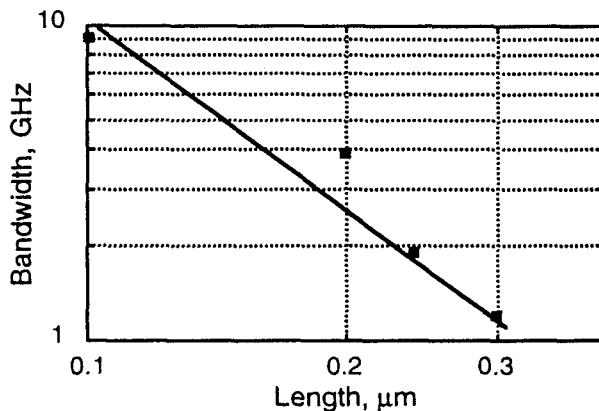

Fig. 3. Bandwidth vs length for devices with different lengths. Solid line is the L^{-2} dependence for the diffusion cooled case. The devices with L = 0.2 μm was twice less resistive as the other two. That was likely the reason that the bandwidth for this device was larger than expected.
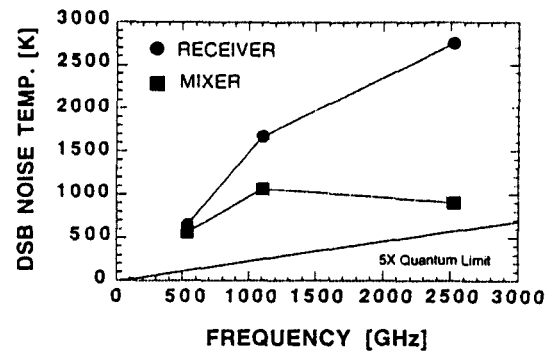

Fig. 4. HEB receiver (circles) and mixer (squares) noise temperature versus frequency for 3 different receivers. The mixer noise is essentially flat over a 2 THz frequency range.

largest bandwidth greater than 9 GHz for a device 0.1 μm long. The mixer noise bandwidth however is generally greater than the signal bandwidth [4,9]. This is the highest bandwidth ever measured for a low-noise bolometer mixer.

IV. RF COUPLING AND LOSSES IN THE MIXERS

The mixer antenna frequency response was measured using a Fourier Transform Spectrometer (FTS). For this measurement, the HEB device operating temperature was set to a value near T_c, and the bias voltage was adjusted to obtain a large direct-detection response in the bolometer. For the double-dipole antenna the center frequency is about 980 GHz and the rf bandwidth is 730 GHz. For the twin slot antenna, the center frequency is about 1900 GHz and the 3-dB bandwidth is approximately 1.1 THz. These results agree with the expected performance for double-dipoles and twin-slots and demonstrate that these antennas still function well up to 2.5 THz.

Y-factor measurements give a noise temperature of 1670 K DSB for the 1.1 THz receiver [5]. To calculate the mixer noise, only the simplest and best measured corrections were made. Removing the amplifier noise and small off-resonant antenna loss would imply a mixer noise of ≤ 950 K. For the 2.5 THz receiver, a best noise temperature of 2500-3000 K was obtained for an IF near 1.4 GHz. Doing similar corrections the mixer noise temperature of about 900 K can be obtained. The LO power absorbed in the device was about 80 nW, and the total *mixer* LO requirement is estimated to be 420 nW (this accounts for the ≈ 7.2 dB of optical and embedding circuit losses [6]). These results at 2.5 THz are 5-times lower noise and 10^4-times lower LO power than competing technologies. Figure 4 summarizes these results along with our previous measurements at 530 GHz [10] and demonstrates that the HEB mixer noise is nearly independent of frequency over a range of at least 2 THz.

Straightforward improvements in antenna design, device impedance match, and use of anti-reflection coatings should result in at least a factor 2 improvement in receiver noise. Thus receiver noise temperature less than about 1000 K should be readily possible up to 3 THz using Nb devices.

The HEB mixer fixed-tuned rf bandwidths of ≈ 50%, discussed above, are many times larger than SIS mixers since the rf impedance of the HEB device is almost purely resistive up to frequencies over 100 THz. The HEB thus provides a broadband resistive match to the broadband planar antennas (using spiral antennas, mixer bandwidths of several octaves should be possible).

2

V. ADVANTAGES OF MATERIALS WITH LOWER CRITICAL TEMPERATURE FOR HEB MIXERS

Currently LO source technology is not as well developed as mixer technology and this puts further demands for improvement of HEB mixers in terms of decreasing the LO power requirements and increasing the IF bandwidth. Also, since theoretically the HEB mixers can achieve quantum limited noise performance, it is of practical interest to find a way to achieve this limiting performance. A proper choice of the device material can create a more optimal combination of mixer parameters.

The diffusion cooling regime can be achieved in most materials as long as the device is made sufficiently short. As seen in Fig. 5, Nb, NbC, and Al all have $D \geq 1$ cm^2/s. For $D = 10$ cm^2/s (a typical value for aluminum) and $L = 0.1$ μm, the calculated diffusion time is ≈ 1 ps which corresponds to an effective mixer bandwidth of 160 GHz. Even taking into account the difference between the theory and experiment, a bandwidth of several tens GHz seems to be quite possible.

A large range of diffusion constants gives flexibility in adjusting the mixer resistance to a desirable value. Indeed, if one tries to increase the bandwidth by using a very clean film, it may happen that the resistivity will be so low that the mixer device will be mismatched with the planar antenna impedance. Such a situation is more likely in Nb which has a higher density of electron states N_ε ($\rho^{-1} = N_\varepsilon e^2 D$) than Al and NbC where the density of states is three times lower than in Nb (see Fig. 6). Therefore one can use cleaner films (= larger bandwidth) of these materials, while maintaining at the same time a suitable resistance for matching to rf embedding circuits.

According to theory [4] the best HEB mixer performance takes place when the thermal fluctuation noise dominates over the Johnson noise. Under these circumstances assuming that the device operates at temperature $T \ll T_c$, the SSB mixer noise temperature for diffusion-cooled mixer, T_M, is given by the following expression: $T_M = 2T_c$. These limits are shown in Fig. 6 (horizontal lines). One can see that the theoretical limit for Al is many times lower than that for higher critical temperature materials. The theory [4] does not consider any quantum phenomena though the quantum noise limit will be important at THz frequencies. A simplistic empirical correction can be made by adding one quantum contribution, $h\nu/k_B$, to the limit of Eq. 3. As a result the

Fig. 6. Theoretical noise temperature limits for different mixer materials. The dash-and-dot line is the quantum limit.

difference in T_M between Al and other HEB mixers becomes smaller but is still significant.

Anther advantage of low-T_c materials is a small required LO power. For $T^2 \ll T_c^2$, $P_{LO} \propto T_c^2$, and one can see that Al with its low T_c (≈ 1.6 K) requires very low LO power (≤ 20 nW) compared to other materials with $T_c \approx 6$-10 K. The bandwidth does not suffer however since it is temperature independent, in contrast to that in phonon-cooled devices. Due to the latter circumstance the diffusion-cooled mixer provides more flexibility in optimization for a particular application.

VI. HIGH-T_c HEB MIXER

Sensitive and tunable terahertz heterodyne receivers are required for several important remote-sensing and in-situ applications, including spectroscopic mapping of the earth's atmosphere, other planetary atmospheres, as well as the gases and chemical composition of comets. Today the only heterodyne instrument available for such long-duration space missions is based on a Schottky-diode mixer (see Fig. 1). The fixed-tuned RF bandwidth is less than 20%, and the required LO power is 1-3 mW which can be provided only by a bulky and power consuming FIR laser at terahertz frequencies.

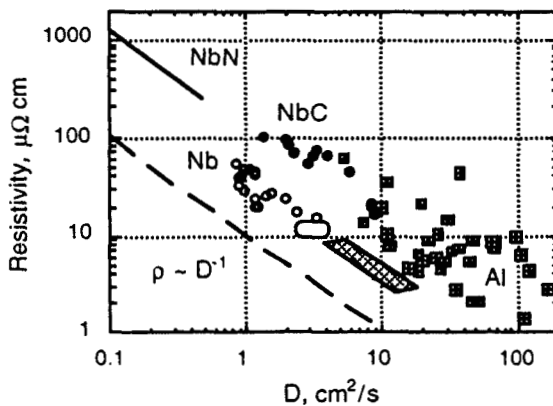During the last few years preliminary heterodyne mixing

Fig. 5. The resistivity vs diffusivity data for different superconducting films. The shaded tetragonal is an extrapolation for some low-resistive Nb film (diffusivity was not measured), the oval represents the range for Nb films used at JPL.
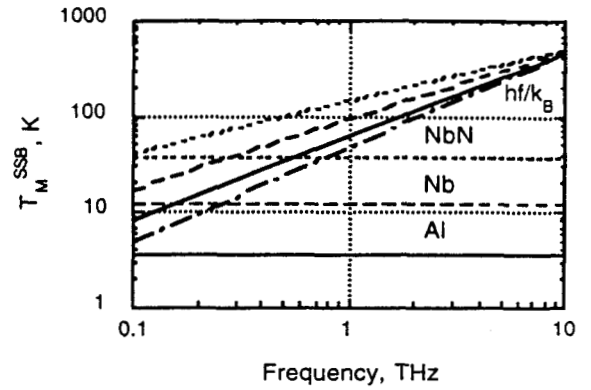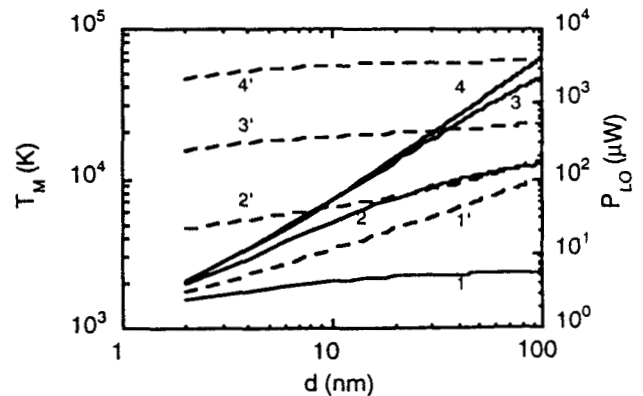

Fig. 7. Size dependence of the mixer noise temperature (solid lines) and optimal LO power (dashes). 1 and 1', $L = 0.1$ μm; 2 and 2', $L = 0.3$ μm; 3 and 3', $L = 1.0$ μm; 4 and 4', $L = 3.0$ μm.

experiments have been performed with large area ($\approx 20 \times 10$ μm^2) high-T_c devices made from a 50-60 nm thick YBCO film [11]. These experiments demonstrated that (a) the mixing mechanism is bolometric (b) the mixing performance does not depend on the radiation frequency (the measurements were done between 30 THz and 300 THz), and (c) the conversion efficiency bandwidth can be as wide as ~100 GHz and is determined by the intrinsic electron-phonon relaxation time in the material.

Our theoretical calculations [12] show that $YBa_2Cu_3O_{7-\delta}$ (YBCO) HEB mixers operating at 66–77 K can perform better than Schottky-diode mixers in terms of both noise temperature and LO power requirements. A distinguishing feature of the present theory is a consideration of the phonon diffusion from the device into the normal metal contacts. This mechanisms significantly increases the thermal conductance between the electron and phonons when the device length L~0.1 μm, allowing for larger amount of the LO power per unit of volume and lower noise temperature of the mixer. Figure 7 shows the size dependence of the noise temperature and the required LO power for an optimized high-T_c mixer device at 66 K for an intermediate frequency $f_{IF} = 2.5$ GHz. One can see that the noise temperature as low as ≈ 2000 K along with the LO power of a few μW might be possible for a 0.1 μm long device fabricated from a 10 nm thick YBCO film.

By now, relatively large, 1×1 μm^2, antenna-couple devices were fabricated from a 20 nm thick YBCO film on an $YAlO_3$ substrate. Very thin quality films, ≤ 20 nm, are required to minimized the phonon escape time from the film and hence improve the thermal conductance which improves the mixer performance. Such films were produced by laser ablation on an $YAlO_3$ substrate with a 20 nm $PrBa_2Cu_3O_{7-\delta}$ (PBCO) buffer layer. The superconducting transition in our devices occurs at ≈ 85 K and the transition width is less than 2 K. A more detailed description of the whole process is given in [13].

Using a CO_2-pumped far-infrared laser, we performed RF tests of the high-T_c devices at 77 K. The amount of LO power needed to maximize the mixing signal as well as the position of the optimal operating point were close to those predicted by theory [12]. However the overall RF coupling to the device was poor. The improvement of optical coupling and tests of submicron-sized devices must be performed to provide a fully convincing "proof of concept" test of this new technology.

VII. SUMMARY

Excellent performance of diffusion-cooled Nb HEB receivers has been demonstrated at 1.1 THz and 2.5 THz with noise temperatures of 1670K and 2750K respectively. The mixer noise performance is shown to be independent of frequency from 0.5 THz to 2.5 THz. The absorbed LO power is 80 nW or less. The ultra-wide rf bandwidths (up to 1 THz) of these HEB mixers if combined with a broadband photomixer LO would allow for the first time the possibility of a single-channel heterodyne receiver with 700 to 1000 GHz of easily-tunable frequency range.

The further development of HEB mixers is seen to go both to lower and to higher temperatures. At subkelvin temperatures HEB devices for radioastronomy applications made from low-T_c materials, such as Al, can demonstrate a quantum limited performance with ≈ 10 nW of required LO power dissipated in the device. At ≈ 70 K submicron size YBCO devices can outperform Schottky-diode mixers since they would require only a few μW of LO power. The natural niche for such mixers would be long duration atmospheric and planetary missions aimed at spectral surveys and mapping of chemical species in atmospheres.

VIII. REFERENCES

[1]   These data are taken from different sources: Schottky diode data are taken from the Proc. 7th Int. Symp. on Space Terahertz Technology (STT-7), University of Virginia, Charlottesville, VA, March 1996; SIS data are from STT-7; NbN HEB data are from STT-7, STT-8, STT-9, J. Kawamura et al., *J. Appl. Phys.* 80, pp. 4232-4234 (1996); *Appl. Phys. Lett.* 70, 1619-1621 (1997), and A.D. Semenov et al., *Appl. Phys. Lett.* 69, 260-262 (1996), G.W. Schwaab, *1998 SPIE Int.Symp. Astronomical Telescopes and Instrum.* (communications); Nb HEB data are from Refs. 5, 6 & 10.

[2]   E.M. Gershenzon, G.N. Gol'tsman, I.G. Gogidze, Y.P. Gusev, A.I. Elant'ev, B.S. Karasik, and A.D. Semenov, "Millimeter and submillimeter range mixer based on electronic heating of superconducting films in the resistive state," *Sverhprovodimost' (KIAE)*, 3(10), 2143-2160 (1990) [*Sov.Phys. Superconductivity*, 3(10), 582-1597 (1990)].

[3]   D.E. Prober, "Superconducting terahertz mixer using a transition-edge microbolometer," *Appl. Phys. Lett.* 62(17), 2119-2121 (1993).

[4]   B.S. Karasik and A.I. Elantiev, "Noise temperature limit of a superconducting hot-electron bolometer mixer," *Appl. Phys. Lett.* 68, 853-855 (1996); "Analysis of the noise performance of a hot-electron superconducting bolometer mixer," *Proc. of the 6th Int. Symp. on Space Terahertz Technology*, 21-23 March 1995, Caltech, Pasadena, pp. 229-246.

[5]   A. Skalare, W.R. McGrath, B. Bumble, H.G. LeDuc, "Measurements with a diffusion-cooled Nb hot-electron bolometer mixer at 1100 GHz", *Proc. 9th Int. Symp. on Space Terahertz Technology*, 17-19 March 1998, Hilton Hotel, Pasadena, pp. 115-120.

[6]   B.S. Karasik, M.C. Gaidis, W.R. McGrath, B. Bumble, H.G. LeDuc, " Low noise in a diffusion-cooled hot-electron mixer at 2.5 THz", *Appl. Phys. Lett.* 71, 1567-1569 (1997).

[7]   B. Bumble and H.G. LeDuc, "Fabrication of a diffusion cooled superconducting hot electron bolometer for THz mixing applications", *IEEE Trans. Appl. Supercond.*, Vol. AS-7, pp. 3560-3563 (1997).

[8]   P.J. Burke, R.J. Schoelkopf, D.E. Prober, A. Skalare, W.R. McGrath, B. bumble, and H.G. LeDuc, "Length scaling of bandwidth and noise in in hot-electron superconducting mixer," *Appl. Phys. Lett.* 68, 3344-3346 (1996).

[9]   R.J. Schoelkopf, P.J. Burke, D.E. Prober, B. Karasik, A. Skalare, W.R. McGrath, M.C. Gaidis, B. Bumble, H.G. LeDuc, "Noise bandwidth of diffusion-cooled hot-electron bolometers", *IEEE Trans. Appl. Supercond.*, Vol. AS-7, pp. 3576-3579 (1997).

[10]   A. Skalare, W.R. McGrath, B. Bumble, H.G. LeDuc, P.J. Burke, A.A. Verheijen, R.J. Schoelkopf, and D.E. Prober, "Large bandwidth and low noise in a diffusion-cooled hot-electron bolometer mixer," *Appl. Phys. Lett.* 68, 1558-1560 (1996).

[11]   M. Lindgren, M.A. Zorin, A. Trifonov, M. Danerud, D. Winkler, B.S. Karasik, G.N. Gol'tsman, and E.M. Gershenzon, "Optical mixing in a patterned $YBa_2Cu_3O_{7-\delta}$ thin films," *Appl. Phys. Lett.* 65, 3398-3400 (1994); V.A. Trifonov, B.S. Karasik, M.A. Zorin, G.N. Gol'tsman, E.M. Gershenzon, M. Lindgren, M. Danerud, and D. Winkler, "9.6 μm wavelength mixing in a patterned $YBa_2Cu_3O_{7-\delta}$ thin films," *Appl. Phys. Lett.* 68, 1418-1420 (1996).

[12]   B.S. Karasik, W.R. McGrath, and M.C. Gaidis, "Analysis of a high-T_c hot-electron mixer for terahertz applications," *J. Appl. Phys.* 81(3), 1581-1589 (1997).

[13]   M.J. Burns, A.W. Kleinsasser, K.A. Delin, R.P. Vasquez, B.S. Karasik, W.R. McGrath, and M.C. Gaidis, "Fabrication of high-Tc hot-electron bolometric mixers for terahertz applications", *IEEE Trans. Appl. Supercond.*, Vol. AS-7, pp. 3564-3567, June 1997.